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Abstract

Disputes between researchers over who deserves credit for technological breakthroughs are not unusual. Few such disputes, however, have attracted as much attention as the arguments surrounding the award of the 2003 Nobel Prize for Medicine. This prize was awarded to Paul Lauterbur and Peter Mansfield to honor "discoveries concerning the development of magnetic resonance imaging" – i.e. MRI. Soon after the award, another scientist, Raymond Damadian, took out full-page advertisements in national newspapers, decrying the award and stating that he should have been included alongside Lauterbur and Mansfield. This technical report examines Damadian's claim from a strictly empirical perspective, by analyzing the impact of Damadian, Lauterbur, Mansfield and others on the development of MRI technology. Impact is measured via citations to their work from subsequent MRI-related patents and scientific papers. The report finds that all three scientists have had a strong impact on the development of MRI, and their early influence in this technology exceeds that of any other scientist. Damadian's impact on MRI patents and papers was greater than that of Lauterbur and Mansfield in the initial, innovative phase of MRI technology; while Mansfield and Lauterbur (especially the former) became more influential in the growth and maturing phases. Given that the Nobel Prize can be awarded to up to three recipients, and is supposed to reward initial discoveries rather than improvements, it thus appears that, from an empirical perspective, the 'natural' solution would have been for all three scientists to share the award. Damadian may thus have been short-changed by the Nobel committee in its decision to omit him from the 2003 Nobel Prize for Medicine.

Introduction

This technical report focuses on the 2003 Nobel Prize for Medicine, which is perhaps one of the most contentious prizes in the history of this award. The recipients of the prize were Paul Lauterbur and Peter Mansfield to honor "discoveries concerning the development of magnetic resonance imaging". Another scientist, Raymond Damadian, was not included in the award and, soon after it was announced, he took out numerous full page advertisements in the *New York Times* and *Washington Post*, denouncing the Nobel Committee, and claiming that he should have been included in the award along with Lauterbur and Mansfield. While disputes over credit for landmark discoveries are commonplace in academic and research circles, these advertisements raised the profile of this particular prize immeasurably, and attracted attention from a much broader segment of the scientific community.

Prior to the 2003 Nobel Prize, Damadian had received numerous different awards related to his magnetic resonance imaging (MRI) research. He is credited with inventing the first MRI scanner and was inducted into the National Inventors Hall of Fame in 1989 for this invention. Damadian was also awarded the National Medal of Technology by President Reagan in 1988, sharing it jointly with Lauterbur for their "independent contributions in conceiving and developing the application of magnetic resonance technology to medical uses, including whole-body scanning and diagnostic imaging". A year later, Damadian was inducted into the National Inventors Hall of Fame for patenting the first MRI scanner; while in 2001 he was awarded the Lemelson-MIT lifetime achievement award for creating the first whole-body scanner and producing the first human body image.

Given Damadian's history of being awarded high-profile prizes (either solo or with Lauterbur) for his MRI research, questions were raised as to why he was not included in the Nobel award. The award can be given to up to three recipients, so including him would not have been at the expense of either Lauterbur or Mansfield. Many of the articles written about the prize focused on the rivalry between the various scientists involved, particularly Damadian and Lauterbur. One major source of contention was that

Lauterbur referenced Damadian's research in his lab notebook, but neglected to do so when the idea in the notebook became his seminal paper published in *Nature* (Matson and Simon, 1996). The absence of such a reference gave the impression that Lauterbur had not built upon Damadian's earlier work. On a more personal level, there have been suggestions that Lauterbur had let it be known that he would not accept the Nobel Prize if Damadian was also awarded (Monastersky, 2003). This has been proposed as a reason why the Nobel committee elected to award the prize to two recipients, rather than the maximum of three. Others have suggested that Damadian may have burned too many bridges with the scientific community, and may have been omitted due to his highly public creationist views (Ruse, 2004).

The purpose of this technical report is to examine, from a strictly empirical perspective, the claim that Damadian should have been included in the Nobel Prize for Medicine in 2003. The report explores the impact of Damadian, Lauterbur, Mansfield and others on the development of MRI technology, with impact measured via citations to their work from subsequent MRI-related patents and scientific papers. While much of the controversy surrounding this award has now abated, largely due to the passage of time, it is still an interesting example of how data science can be used to address issues in scientific and technological development[1].

Scientific Background

Before analyzing the empirical data, it is worthwhile examining the scientific background to the 2003 Nobel Prize controversy, in order to provide some context for the analysis. We concentrate on the three main individuals associated with the controversy – the two prize recipients (Lauterbur; Mansfield) and the non-recipient (Damadian).

Damadian is widely credited with the initial research that brought magnetic resonance imaging from the fields of chemistry and physics into the field of medicine (Wehrli, 1992; Partain et al. 2004; McRobbie et al. 2003). In particular, his early paper published in *Science* (Damadian, 1971) reported measurable relaxation time differences between cancerous and non-cancerous tissue, and was the first example of using MRI (at that time referred to as NMR[2]) for medical purposes. Damadian also filed the first U.S. Patent for an MRI machine (filed in 1972; granted in 1974 as US #3,789,832). In a 1997 patent infringement case brought by Damadian's company against General Electric, the Federal Court affirmed that, at that time, all MRI machines relied upon relaxation time differences for imaging (Federal Reporter, 1997).

Lauterbur, in his seminal paper in *Nature* (Lauterbur, 1973), introduced the idea of using field gradients to improve the speed and efficiency of MRI imaging. This is regarded as a key development in making MRI feasible from a practical perspective, especially in terms of time and cost. Indeed, in his own later MRI

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[1] This report is based largely on work I did in 2004 as part of a study commissioned by Fonar (Raymond Damadian's company) when I was employed as an analyst at CHI Research Inc (which accepted the commission on the strict basis that the analysis would be impartial, and not guided by Fonar in any way). I left CHI in 2004 to co-found 1790 Analytics, and I am now an Assistant Professor of Computer Science and Data Science at Rowan University. In 2015, Dan Culver, the Director of Communications at Fonar, informed me that the CHI study was never completed, and gave me my old data files (property of Fonar as work-for-hire) with the understanding that I could do what I wanted with them. This technical report represents a summary of the findings from the incomplete report. The report is not funded by Fonar, Rowan, 1790, or anyone else at this point. All of the opinions expressed in this paper, right or wrong, are my own.

[2] Researchers in the early 1970's spoke of NMR (Nuclear Magnetic Resonance) rather than MRI; the latter term started to gain popular usage in the late 1970's when researchers decided that the use of the word 'nuclear' may scare people away from the new technology.

machines, Damadian incorporated the field gradients suggested by Lauterbur, rather than the field-focused scanning used in his early machines.

Mansfield is credited with inventing slice-by-slice imaging for MRI, and developing an MRI protocol named echo-planar imaging, which enabled images to be collected many times faster than was possible previously. He is also credited with advancing understanding how MRI images can be analyzed mathematically, thus improving their usability (Mansfield and Grannell, 1973; Mansfield, 1977).

Supporters of Damadian's position with regard to the Nobel Prize often point to the statement in Alfred Nobel's will that the award should go to discoveries and not to improvements. They argue that Lauterbur's gradient method and Mansfield's echo-planar technique were important landmarks, but they were in actuality improvements of MRI. The initial discovery of how MRI could be used in medical imaging is an idea whose credit should rest with Damadian. Without this discovery, other researchers (including Lauterbur and Mansfield) would have continued to use NMR in chemistry and physics, but would have been unlikely to consider its potential medical application. Also, as is typical of many scientific pioneers, Damadian had to fight a great deal of skepticism, both from funding bodies and work colleagues, about the idea of using NMR/MRI to scan human patients (Kleinfield, 1985).

Meanwhile, supporters of the Nobel committee's decision to omit Damadian highlight the fact that the award was given for 'MR *imaging*', with the inclusion of the latter word crucial. They argue that Damadian was indeed the first to point out that differences in relaxation times between cancerous versus non-cancerous tissues could be detected using MRI. However, his approach to imaging was too slow and clumsy, and represented a technical dead-end that would have remained an intellectual curiosity if not for the breakthroughs in imaging made by Lauterbur and Mansfield. Damadian supporters counter that he found the signal and without the signal there is no image.

This technical report attempts to evaluate the relative influence of discoveries made by Damadian, Lauterbur, Mansfield and others upon subsequent developments in MRI technology. The purpose is to provide an objective measure of these scientists' roles, and thus help address the question of whether – putting all personal and reputational issues aside – Damadian did indeed deserve to share the Nobel Prize in 2003.

Methodology

Citation Analysis

This technical report describes the results of an empirical analysis designed to identify the most influential scientists in the early development of MRI technology. As such, the analysis provides insights into which scientists may have been deserving of the 2003 Nobel Prize for Medicine, which was awarded for this technology.

The analysis is based on an examination of scholarly documents – i.e. scientific papers and patents – related to MRI technology, with a particular focus on how these documents trace their lineage back to the work of early researchers in the field. This tracing is achieved using a bibliometric technique known as *citation analysis*. The origins of large scale citation analysis lie with the work of Eugene Garfield, who first proposed the Science Citation Index in the 1950's as a tool to increase the power of scientists to retrieve relevant scientific papers (Garfield, 1955). Garfield also pointed out that, in evaluating science, it would be useful to be able to trace the impact of a given paper, based on references it received from subsequent scientific papers. This forms perhaps the key premise of citation analysis – i.e. that a reference from one paper to another (or from one patent to another) denotes that the cited paper has had some degree of influence upon the development of the citing paper. Following on from this, the more references a particular paper (or patent) has received, the greater its assumed influence.

The relationship between citation counts to papers and measures of scientific and technological merit has been validated in many different studies. Narin (1976) summarized 24 such studies, all of which supported the idea that high citation in the scientific literature is associated with peer rankings of scientific papers and research institutions. With respect to Nobel prizes, Inhaber and Przednowek (1976) noted that the number of citations received by the work of Nobel laureates in physics was an order of magnitude higher than the number received by the work of other scientists. Similarly, Garfield (1986) studied 125 Nobel laureates in the fields of chemistry, physics, physiology, and medicine, and found that 80 percent had published what he called citation classics – i.e. papers among the most 1,000 most cited over the period 1961-1982.

Numerous validation studies have also established a positive relationship between citations to patents and measures of technological merit – for an overview of such studies, see Breitzman and Mogee (2002). For example, Carpenter et al (1981) reported that patents associated with the IR-100 award (which honored the 100 most significant technical products of the year) received twice as many citations as a control set of patents of the same age and in the same technologies. Meanwhile, Breitzman and Narin (1996) examined citation frequencies associated with three 'special' categories of patents: those listed in the National Inventor's Hall of Fame; those denoted as having Historical Significance in a list prepared by the U.S. Department of Commerce for the USPTO bicentennial; and those designated as 'pioneering' patents by the Federal District Court. The study found that pioneering patents are cited almost seven times as often as expected; Hall of Fame patents are cited more than six times as often as expected; and historically significant patents almost 2.5 times as often as expected.

In the analysis described in this report, citations were used to trace the influence of scientists associated with the early developments in MRI technology. One specific question examined was which scientists produced the most influential early research in this technology, as measured by citations to their patents and scientific papers.

Construction of Data Set

The data set for this analysis consisted of U.S. patents related to MRI technology issued between 1972 and 2003; and journal publications related to MRI technology published between 1970 and 2003. Below is a description of the process used to locate relevant patents and papers.

With respect to patents, the US patent office has an extensive classification scheme that categorizes patents according to their technological focus (or, more correctly, their 'art unit'). There is also an international patent classification scheme that performs a similar task. For this study, we used a combination of US patent classifications, international patent classifications, and keywords to locate patents relevant to MRI technology. There were approximately 4,500 such patents issued between 1972 and 2003, and these formed the basis for the patent element of the study.

The process for identifying relevant scientific papers was much less straightforward, especially since an equivalent to the patent classification scheme does not exist. Also the papers were sourced externally from Thomson ISI (now ThomsonReuters), leading to issues of cost and license restrictions. In the initial step, Thomson analysts used a combination of journals, keywords, and subfield classifications to locate a super-set of 380,000 NMR/MRI papers going back to 1970. This super-set contained NMR/MRI papers directed to medical applications (which are relevant to this study), but also NMR papers describing chemistry and physics applications (which are not relevant), since there was no easy way for Thomson to eliminate the latter from the initial set. We therefore had to differentiate between these papers ourselves.

Identifying the papers related to medical imaging rather than chemistry and physics was a significant undertaking, since reading 380,000+ titles was not practical. The process involved three stages. In the initial step, we used the journal-based categories developed by Thomson. This enabled us to locate many of the relevant papers, especially those in dedicated medical journals. However, many of the key papers were in multidisciplinary journals like *Science* or *Nature*, and a journal-based approach would not work for these papers. Also, many of the early medical NMR/MRI papers appeared in the same journals that the NMR chemistry/physics papers had always appeared. We therefore added two more steps to augment the initial categorization.

Step 2 was based on keywords. After the initial step, papers in specialty medical journals had been identified. It was thus possible to extract keywords that appear particularly frequently in these medical papers, relative to the remaining papers. We also identified keywords that appear frequently in the remaining papers, but not in the medical papers. Table 1 shows a sample of these two sets of keywords. By searching the uncategorized papers for these terms, we were able to classify additional papers as medical versus non-medical. These include early medical MRI papers in NMR-related journals, and medical MRI papers in multidisciplinary journals.

The final step used patterns of cross-citations between the medical MRI papers and the non-medical MRI/NMR papers classified in the first two steps. Table 2 reveals that papers in the medical MRI category reference an average of 9.6 earlier papers (8.8 medical MRI papers and 0.8 non-medical MRI papers). Meanwhile, the non-medical MRI papers reference an average of 0.3 medical MRI papers and 8.2 non-medical MRI papers. This suggests that medical MRI papers reference non-medical MRI papers infrequently, and vice versa.

Hence, papers categorized as non-medical that reference more medical MRI papers than non-medical MRI papers were likely to be mis-categorized. Therefore, in the final categorization, we moved non-medical MRI papers to the medical MRI category if they referenced more medical MRI papers than non-medical MRI papers. Medical MRI papers that reference mostly nonmedical MRI papers may also be mis-categorized, although this is less reliable, since medical MRI papers were so infrequent prior to 1975 that the bulk of the references from these papers were to non-medical MRI papers. We therefore elected not to move any papers from the medical MRI to the non-medical MRI category based on referencing patterns.

In total, we identified approximately 100,000 medical MRI papers (although some of the early papers may not actually be medical papers). Due to licensing restrictions, we agreed to restrict our analysis samples containing no more than 25,000 papers. Files containing the remaining papers were destroyed to protect Thomson's intellectual property. These samples form the basis for the publication analysis outlined below. For ease of presentation, in the remainder of this report, papers in these samples are referred to as 'MRI papers', rather than the more awkward 'medical MRI papers'.

Results

This section of the report outlines the results of our analysis examining the impact of pioneering scientists in MRI technology. It should be noted that these results end in 2003, which was the last full year when the analysis was carried out, and when the Nobel Prize in question was awarded. Hence, the data used in the analysis is similar to that which would have been available to the Nobel committee when they decided upon their award.

Identifying the Innovative Phase in MRI Technology

As noted earlier, Nobel Prizes are supposed to be awarded to technological discoveries, not incremental improvements. In searching for the most influential early MRI patents and papers, it was thus necessary to define what is meant by 'early'. To do this, we fitted S-curves to the pattern of patenting and publishing over time related to MRI technology. These S-curves are widely used to model the three periods of technological development (innovation, growth, and maturity). In this study, we wanted to concentrate on the first of these three periods – i.e. the period of innovation.

Figure 1 shows patent activity in MRI technology by year of patent application. The trend is a little noisy, but fitting a polynomial to the data reveals that it does follow an S-Curve. The innovation period consists of sporadic patenting from 1972-82. Then, a critical mass was reached and the number of MRI patent applications grew rapidly from 1983-91. After 1991, the number of patent applications continued to grow but at a slower rate, suggesting the technology had begun to mature. This produces three distinct periods: innovation (1972-1982); growth (1983-1991); maturity (1992 onwards).

Figure 2 shows the number of MRI papers per year between 1970 through 1990. There are only a few papers per year in the 1970s, then hundreds followed by thousands per year in the 1980s. The trend in Figure 2 again follows an S-Curve with an innovation stage (1970-1980); a growth stage (1981-1990); and a mature stage (1991 onwards).

Hence, the innovative periods that form the focus of this study are 1972-1982 (for patents) and 1970-1980 (for papers). The innovative period for patents is slightly later than that for papers, since the pendency period for patents (i.e. the time between patent application and issuance) is longer than the in-press period for papers.

Impact of Pioneering Scientists on MRI-Related Patents

The purpose of this section of the report is to determine the influence of early discoveries related to MRI technology upon subsequent patents in this technology. These early discoveries are defined as those made during the innovative period for MRI technology (1970-1980 for papers; 1972-1982 for patents). Table 3 lists the 35 U.S. patents related to MRI technology filed between 1972 and 1982. This table reveals that Damadian's patent US #3,789,832 was the first applied for within this technology. Table 4 contains a list of all MRI papers published between 1970 and 1980 that have been cited by at least one subsequent MRI patent. These papers are included in the analysis because some early discoveries were published rather than patented. For example, Lauterbur's work became a paper instead of a patent, since his institution at the time (SUNY Stony Brook) thought that the invention was not worth patenting (Monastersky, 2003).

From these two tables, we identified scientists with at least one patent or paper from 1975 or earlier, since our focus is on initial discovery (in line with the Nobel criteria). Table 5 lists the scientists with at least one patent or paper in that early period. There are five such scientists (Damadian; Weisman; Lauterbur; Abe; Mansfield). These scientists are prime candidates for recognition as being responsible for the discovery of medical MRI technology (and thus potential candidates for the Nobel Prize for this technology). We therefore explored the impact of each of these scientists' documents, both on each other and on MRI patents in general.

With respect to the influence of the pioneering MRI scientists on each other, Figure 3 shows the citation links between their early MRI documents. This figure reveals that Damadian is cited directly by three out of the four other scientists. The exception is Lauterbur, whose *Nature* paper failed to cite Damadian (even though his lab notebook did so, as discussed earlier). Damadian has an advantageous position in this figure, since he has the earliest documents, and by definition citations can only go backwards in time. Having said this, it is noteworthy that Damadian is the only scientist referenced this extensively, with Abe cited only by Mansfield; Weisman by Lauterbur; and Lauterbur not at all. Mansfield is also uncited in Figure 3, but this is inevitable since he has the most recent documents.

The right-hand columns in Table 3 show the results of extending the analysis beyond the influence of the pioneering scientists on each other, to cover all patents in the innovative period. It also extends the analysis to consider both direct citations (i.e. where a first selected document references a second selected document) and indirect citations (i.e. where a first selected document references a document that in turn references a second selected document). These columns in Table 3 show which of the 35 MRI patents from the innovative period have direct and indirect citation links to the pre-1976 documents of Damadian, Abe, Lauterbur and Mansfield (Weisman is not listed, since none of the 35 patents are linked to his paper).

Table 6 summarizes these direct citations (upper section of the table) and indirect citation counts (lower section) from the innovative period. It reveals that 15 out of the 35 patents in the innovative period cite Damadian directly. This is second only to Mansfield (19 citing patents). Meanwhile, 32 out of the 35 patents are linked indirectly to Damadian through citations. This is more than any of the other four pioneering MRI scientists. It is notable that the number of citations from MRI patents in the innovative period to Lauterbur, both direct and indirect, is relatively low.

Table 6 also extends the analysis to cover citations from patents filed in the growth (1983-90) and maturing (1991-2003) phases of MRI technology. In terms of direct citations, Damadian is again second to Mansfield in the growth phase, but leads by a wide margin in the maturing phase. Damadian is also second to Mansfield in both the growth and maturing phase in terms of indirect citations (although, by the maturing phase, the citation network had become so interconnected that the results for indirect citations are very similar for each scientist).

Overall, the results from the patent citation analysis suggest that Damadian had the strongest impact upon the early work of the other pioneering MRI researchers. More broadly, Damadian and Mansfield had the strongest impact on developments across MRI technology.

Impact of Pioneering Scientists on MRI-Related Papers

This section of the report is similar to the previous one, except that it focuses on the influence of pioneering MRI scientists on subsequent papers, rather than subsequent patents. As in the previous section, the analysis again explores the influence of the pioneering scientists upon each other; on the innovative period in MRI technology in general; and on the growth and maturing phases of MRI technology.

Between 1970 and 1980 (the innovative period for MRI technology based on publications), there were a total of 655 MRI papers published. Our initial step was to identify the most influential of these papers, and to determine the scientists responsible for them. These scientists could be considered to be pioneers in MRI research, based on their influence on subsequent MRI-related papers. Table 7 contains a list of all MRI papers published between 1970 and 1980 that have received at least 25 citations, with at least three of these citations being from papers published in the innovative period.

Several authors are prominent in Table 7, notably Damadian, Lauterbur, Mansfield, Hollis, and Weisman. With the exception of the inclusion of Hollis instead of Abe, this is the same list of pioneering MRI scientists located in the analysis of MRI patents. This further supports the idea of there being a group of scientists – specifically Damadian, Lauterbur, Mansfield and Weisman – who could be considered prime candidates for the Nobel Prize, given their association with key early MRI discoveries.

Table 8 is a subset of Table 7, containing the papers of Damadian, Lauterbur, Mansfield, Hollis, and Weisman. Among these scientists, Damadian and Weisman have the earliest papers, while Damadian and Mansfield have the most papers in the innovation period. From a citation perspective, two papers in Table 8 stand out. The first is Lauterbur's 1973 paper in *Nature*. This paper has been cited by 1,027 subsequent papers, the most of any paper in Table 8. The second paper is Damadian's 1971 paper in *Science*, which has been cited by 753 subsequent papers, second only to Lauterbur's paper. Having said this, the Damadian paper received more citations than the Lauterbur paper during the innovative period (88 versus 52). This suggests that Damadian's research had a greater early impact than Lauterbur's, while the latter's influence increased more rapidly in the growth and maturing phases of MRI technology. In terms of overall impact, Damadian's work has been cited most frequently, with his 13 papers receiving a total of 1,548 citations (215 from papers published in the innovative period). Mansfield is second (11 papers; 1,295 total citations; 141 citations from innovative period) and Lauterbur third (3 papers; 1,213 total citations; 85 citations from innovative period), followed by Hollis and Weisman.

Table 9 provides more detail on the impact of the five pioneering scientists during the innovative period. The left-hand section of the table shows how many of the 655 papers published during this period reference each of the five scientists. Damadian was referenced by 109 of these papers (which provided a total of 215 citations to his work, since some papers referenced multiple Damadian papers). This is almost twice the number of citing papers for the second-placed scientist – Lauterbur with 66.

The center section of Table 9 explores citations from high-impact MRI papers published during the innovative period (defined as papers that have received at least 25 citations; there are 135 such papers). Again, Damadian is cited by the largest number of these 135 high-impact papers (57), followed by Lauterbur (38), Mansfield (34) and Hollis (34). When indirect citations are included, Damadian is linked to 95 out of the 135 high-impact papers, the most of any of the five pioneering scientists.

The right hand section of Table 9 examines the influence of the five pioneering scientists upon each other. Specifically it examines citation links between 35 early high-impact MRI papers produced by these scientists, and listed in Table 8. Twenty-three out of these 35 papers cite Damadian directly, the most for any of the scientists. Mansfield is second with 15 citing papers, followed by Lauterbur (14) and Weisman (13). It is also notable that all 35 of these papers are linked to Damadian via indirect citations, the only one of the scientists for which this is the case. These citation links between the pioneering scientists are also shown visually in Figures 4 and 5 (the former with self-citations, the latter without). These figures reveal that all of the papers are linked directly or indirectly to Damadian's 1971 *Science* paper. They also reveal that Mansfield's work built heavily on Damadian and Lauterbur; while Hollis built heavily on Damadian (and vice-versa).

Moving beyond the innovative period, we also examined the influence of the five pioneering MRI scientists on the growth and maturing phases of this technology (1981-1990; 1991-2003). Due to licensing restrictions with the Thomson data, we based this analysis on a sample of papers from these periods. The sample consisted of all papers from each period that have received at least 50 citations from subsequent papers. Hence, the analysis examines the influence of the pioneering MRI scientists on the most high-impact MRI papers published during the growth and maturing phases.

There were 915 MRI papers published between 1981 and 1990 that have been cited by at least 50 subsequent papers. Fifty-two of these papers reference Damadian's early papers, 45 reference Lauterbur and 39 reference Mansfield. Meanwhile, between 1991 and 2003, there were 4,125 MRI papers published that have been cited by at least 50 subsequent papers. Out of these 4,125 papers, 67 reference Mansfield directly, 12 reference Lauterbur, and only four reference Damadian. The figures for indirect citations are similar for all five pioneering scientists in both 1981-1990 and 1991-2003, which is probably due to the citation network becoming heavily interconnected as MRI technology matured.

The results from the growth and maturing phases suggest that the direct influence of the pioneering scientists' research decreased over time. In many ways, this is a reflection of the incremental nature of scientific development (after the initial discoveries are made), and the citation practices associated with this development. In particular, over time, researchers become less likely to reference initial discoveries that may be decades old, and well-established in the scientific community.

Having said this, it is interesting to note that both Mansfield and Lauterbur were referenced more frequently than Damadian in the maturing phase of MRI technology, having lagged behind him in the innovative and growth phases (see Figure 6). Mansfield in particular became more influential, which may be due to the increasing prevalence of echo-planar imaging, which he first proposed. It is worth noting that it was during this maturing phase that the Nobel Prize was awarded, so the influence of Lauterbur and Mansfield may have appeared particularly strong relative to Damadian.

Overall, the analysis of scientific papers suggests that Damadian, Lauterbur and Mansfield stand out in terms of their impact on developments in MRI technology. Damadian was particularly influential in the innovative period of the technology, with all of the high-impact papers authored by the other pioneering scientists in the field linked either directly or indirectly to his initial *Science* paper. As the technology developed, Mansfield in particular became more influential, as his echo-planar imaging technique became feasible from a practical perspective.

Conclusions

The results outlined above highlight the strong influence of a small group of pioneering scientists on the development of MRI technology. In particular, three such scientists stand out in terms of their impact on MRI-related patents and papers – Damadian, Lauterbur and Mansfield. The nature of each of their impacts differs somewhat. Damadian had the strongest influence on the other pioneering scientists; Lauterbur had the most influential single scientific paper; and Mansfield's impact on MRI technology has been particularly strong as it has matured.

These differences in impact are important in the context of the criteria for the Nobel Prize, particularly their focus on initial discovery. Supporters of Damadian's position that he should have shared the award suggest that Damadian's finding that NMR/MRI could be used to differentiate between cancerous and non-cancerous tissue was the key discovery that first alerted scientists to the medical possibilities of MRI. Without this discovery, these scientists (including Lauterbur and Mansfield) may simply have continued their NMR research in chemistry and physics. The empirical results presented here suggest that this argument has a great deal of merit, as all of the other pioneering scientists build more extensively on Damadian's initial research than on the research of the other pioneers. This is not in any way to denigrate the contribution of either Lauterbur or Mansfield, the two recipients of the Nobel Prize. Citation patterns to both of their seminal works point to their vital contributions in making MRI technology a widely-used medical technique – Lauterbur in his application of field gradients, and Mansfield in his development of echo-planar imaging.

Much has been written by scientific commentators both for and against the idea of Damadian sharing the 2003 Nobel Prize for his MRI research. Many of their opinions center around exactly what constitutes the 'key discovery' in MRI – i.e. whether it was Damadian's discovery that MRI could differentiate between cancerous and non-cancerous tissue; or Lauterbur's and Mansfield's discoveries of ways to generate usable images quickly and effectively. Indeed, the rival scientists themselves are willing to concede each other's contribution as such. Damadian stated that "Lauterbur took his [Damadian's] numerical findings and converted them into pixel intensities to create an image"; while Lauterbur credited Damadian for "coming up with the idea that testing differences in magnetic relaxation time could be used to noninvasively diagnose cancers" (Brice 2003).

From a purely empirical perspective, it would appear that there were three key scientists responsible for developing the foundations of MRI technology as it existed when the award was made – Damadian, Lauterbur and Mansfield. Given that the award can have a maximum of three recipients, it would therefore seem 'natural' for these three scientists to share it. As such, it appears that Damadian may have been short-changed by the Nobel committee in its decision to omit him from the 2003 Nobel Prize for Medicine.

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Partain et al., "The 2003 Nobel Prize for MRI: Significance and Impact," *Journal of Magnetic Resonance Imaging*, 19:515-526:2004.

Ruse, "The Nobel Prize in Medicine—Was there a religious factor in this year's (non) selection?", *Metanexus Online Journal*, March 16, 2004

Wehrli, *Physics Today*, June 1992.

Table 1: Sample of keywords used to adjust initial categorization

(Full word lists contain some 2000 words for each list)

Words appearing frequently in Medical NMR papers and not in Non-Medical NMR papers
Spinal
Sclerosis
Angiography
CT
Lesions
Artery
Intracranial
Segmentation
Surgery
Medical
Cervical
Epilepsy
Cord
Temporal
Cyst
Carotid
Children
Surgical
Perfusion
Injury
Malignant
Ventricular
Guided
Ischemic
Carcinoma
Breast
Cortical
Ultrasound
Pituitary
Neuroimaging
Knee
Aneurysm

Words appearing frequently in Non-Medical NMR papers and not in Medical NMR papers
Derivatives
Conformational
Polymers
Conformation
Polymerization
Crystal
Chemistry
Copolymers
Solvent
Aromatic
Catalysts
Zeolites
Zeolite
Crystalline
Nitrogen
Substituent
Ligands
Lignin
Phenyl
Ligand
Dond
Conformations
Stereochemistry
Chiral
Lanthanide
Mas
Silica
Dimethyl
Alkyl
Aryl
Salts
Crystals

Table 2: Referencing patterns for Medical NMR and Non-Medical NMR papers

	Avg. Refs to Medical NMR Papers	Avg. Refs to Non-Medical NMR Papers
Medical NMR Papers	8.8	0.8
Non-Medical NMR Papers	0.3	8.2

Table 3: First 35 Patents in Medical MRI Technology (Application Year 1972-82)

Patent	Inventor(s)	Applic. Year	Title	Assignee	Damadian		Abe		Lauterbur		Mansfield	
					Direct	Indirect	Direct	Indirect	Direct	Indirect	Direct	Indirect
03789832	R.Damadian	1972	Apparatus And Method For Detecting Cancer In Tissue	•• Unassigned ••	1	1	0	0	0	0	0	0
03932805	Z.Abe; K.Tanaka; M.Hotta; M.Lmai	1973	Method Of Obtaining Internal Information Of A Measuring Target From The Out-Side By The Application Of A Nuclear Magnetic Resonance	Kichizo Niwa	1	1	1	1	0	0	0	0
4021726	A.Garroway; P.Grannell; P.Mansfield	1975	Image Formation Using Nuclear Magnetic Resonance	National Research Development Corp	0	1	1	1	0	0	1	1
04115730	P.Mansfield	1977	Nuclear Magnetic Resonance Apparatus And Methods	National Research Development Corp	1	1	1	1	0	0	1	1
04165479	P.Mansfield	1977	Nuclear Magnetic Resonance Apparatus And Methods	National Research Development Corp	0	1	0	1	0	0	1	1
04240439	Z.Abe; K.Tanaka; F.Sano	1978	Method Of Obtaining Information Of A Specified Or Target Area Of A Living Body Near Its Skin Surface By The Application Of A Nuclear	Hokkaido University	1	1	1	1	0	0	0	0
04354499	R.Damadian	1979	Apparatus And Method For Nuclear Magnetic Resonance Scanning And Imaging	•• Unassigned ••	1	1	1	1	1	1	1	1
04254778	H.Clow; P.Waiters; W.Percivai	1979	Imaging Svstems	Philips	1	1	0	0	0	0	1	1
04300096	C.Harrison; I.Young	1979	Imaging Systerns	Philips	1	1	1	1	0	0	1	1
04384255	I.Young; C.Harrison	1980	Nuclear Magnetic Resonance Systems	Philips	0	1	0	1	0	0	1	1
04390840	A.Ganssen; A.Oppelt; W.Loeffler	1980	Zeugmatography Process	Siemens Ag	1	1	1	1	1	1	1	1
04398150	Y.Barjhoux; H.Saint Jaimes; J.Taquin	1981	Ironless High-Homogenety Magnet And Its Application To Nuclear Magnetic Resonance Imaging	Thales Group	0	0	0	0	0	0	0	0
04411270	R.Damadian	1981	Apparatus And Method For Nuclear Magnetic Resonance Scanning And Mapping	•• Unassigned ••	1	1	0	1	0	1	1	1
04417209	G.Hounsfield	1981	Nuclear Magnetic Resonance Apparatus	Philips	0	1	0	1	0	0	0	1
04418316	I.Youna: G.Hounsfield; M.Burl	1981	Nuclear Magnetic Resonance Apparatus	Phiiips	0	0	0	0	0	0	0	0
04422042	H.Suaimoto	1981	Nuclear Resonance Apparatus Including Means For Rotating A Magnetic Field	Toshiba Corooration	1	1	0	1	0	1	0	1
04424488	G.Hounsfield	1981	Nuclear Magnetic Resonance Apparatus	Phillips	0	1	0	1	0	0	1	1
04425547	H.Suaimoto	1981	Nuclear Magnetic Resonance Apparatus Having Means For Compensating A Projecting Signal	Toshiba Corporation	1	1	0	1	1	1	0	1
04429277	H.Suaimoto	1981	Nuclear Magnetic Resonance Apparatus Utilizing Multiple Magnetic Fields	Toshiba Corporation	1	1	1	1	0	0	0	0
04458203	I.Youna	1981	Nuclear Magnetic Resonance Imaging	Philips	0	1	0	1	0	0	0	1
04471305	L.Crooks; J.Hoenninger; M.Arakawa	1981	Method And Apparatus For Rapid NMR Imaging Of Nuclear Parameters With An Object	University Of California	0	1	0	1	0	1	1	1
04486708	A.Macovski	1981	Selective Material Projection Imaging System Using Nuclear Magnelic Resonance	•• Unassigned ••	0	1	0	1	0	0	1	1
04528985	A.Macovski	1981	Blood Vessel Imaging System Using Nuclear Magnetic Resonance	•• Unassigned ••	1	1	1	1	0	1	0	1
04431968	W.Edelstein; P.Bottomlev	1982	Method Of Three-Dimensional NMR Imaging Using Selective Excitation	General Electric Co	0	1	0	1	0	0	0	1
04441502	B.Chance	1982	Nmr Syslem For Determining Relationship Between Work Output And Oxidative Phosphorylation Capability In An Exercising Body Member	Phosoho-Energetics	1	1	0	1	0	1	1	1
04443760	W.Edelstein; P.Bottomlev	1982	Use Of Phase Alternated RF Pulses To Eliminate Effects Of Spurious Free Induction Decay Caused By Imperfect 180 Degree Rf Pulses	General Electric Co	0	1	0	1	0	0	0	1
04452250	B.Chance; J.Leiah; S.Eleff	1982	Nmr System For The Non-Invasive Study Of Phosphorus Metabilism	Phosoho-Energetics	1	1	0	1	0	1	1	1
04471306	W.Edelstein; P.Bottomley	1982	Method Of Nmr Imaging Which Overcomes T+HD 2+B • Effects In An Inhomogeneous Static Magnetic Field	General Electric Co	0	1	0	1	0	0	1	1
04484138	P.Bottomlev; W.Edelstein	1982	Method Of Eliminating Effects Of Spurious Free Induction Decay NMR Signal Caused By Imperfect 180 Degrees RF Pulses	General Electric Co	0	1	0	1	0	0	0	1
04506223	P.Bottomley; W.Edelstein	1982	Method For Performing Two-Dimensional And Three-Dimensional Chemical Shift Imaging	General Electric Co	0	1	0	1	0	0	0	1
04509011	H.Sugimoto; K.Satoh	1982	Nuclear Magnetic Resonance Diagnostic Apparatus	Toshiba Corporation	0	1	0	1	0	0	1	1
04509015	R.Ordidge; P.Mansfield	1982	Nuclear Magnetic Resonance Methods	•• Unassigned ••	0	1	0	1	0	0	1	1
04516074	H.Sugimoto	1982	Nuclear Magnetic Resonance Diagnostic Apparatus	Toshiba Corporation	0	1	0	1	0	1	0	1
04527124	C.Van Uijen	1982	Method Of And Device For Determining A Nuclear Magnetization Distribution In A Part Of A Body	Philips	0	1	0	1	0	1	1	1
04551678	T.Morgan; M.Willcott	1982	Phantom For Nuclear Magnetic Resonance Machine	Universily Of Texas	0	0	0	0	0	0	1	1
				Totals:	15	32	9	30	3	11	19	29

Table 4: 1971-82 Medical NMR Papers Referenced in At Least One US MRI Patent Granted through 2004

First Author	Pub Year	Journal	Page	Title
R.Damadian	1971	*Science*	1151	Tumor Detection by Nuclear Magnetic Resonance
I.Weisman	1972	*Science*	1288	Recognition Of Cancer In-Vivo By Nuclear Magnetic-Resonance
P.Lauterbur	1973	*Nature*	190	Image Formation by Induced Local Interactions: Examples EmploYing Nuclear Magnetic Resonance
R.Damadian	1974	*PNAS*	1471	Human Tumors Detected By Nuclear Magnetic Resonance
P.Mansfield	1976	*J Phys E*	271	Fast Scan Proton Density Imaging By NMR
R.Damadian	1976	*Phys Chem & Phys*	61	Tumor Imaging In A Live Animal By Field Focusing Nmr (Fonar)
R.Damadian	1976	*Science*	1430	Field Focusing Nuclear Magnetic Resonance (FONAR): Visualization of a Tumor in a Live Animal
P.Mansfield	1976	*Contemp Phys*	553	Proton Spin Imaging By Nuclear Magnetic Resonance
P.Mansfield	1976	*J Phys C*	409	Planar spin imaging by NMR
R.Damadian	1977	*Phys Chem & Phys*	97	NMR In Cancer: Xvi Fonar Image Of The Live Human Body
P.Mansfield	1977	*J Mag Res*	101	Planar spin imaging by NMR
P.Mansfield	1977	*J Phys C*	55	Multi-Planar Image Formation Using NMR Spin Echoes
R.Damadian	1978	*Naturwissenschaften*	250	Field-Focusing Nuclear Magnetic Resonance
P.Lauterbur	1978	*Front Bio Energ*	752	Augmentation Of Tissue Water Proton Spin-Latiice Relaxation Rates By In Vivo Addition Of Paramagnetic Ions
P.Mansfield	1978	*J Mag Res*	355	Biological And Medical Imaging By NMR
P.Mansfield	1979	*J Mag Res*	261	Selective Pulses In Nmr Imaging: A Reply To Criticism
P. Lauterbur	1980	*Phil. Trans. R. Soc. Lond*	483	Progress In NMR Zeugmatographic Imaging
P. Mansfield	1982	*Adv Mag Res*	232	NMR Imaging In Biomedicine

Table 5: Who Discovered MRI? Potential Candidates based on Early Papers and Patents

Candidate	# Papers 1971-82	# Patents 1971-82	First Paper	First Patent
R. Damadian	6	2	1971	1972
I. Weisman	1	-	1972	-
P. Lauterbur	4	-	1973	-
Z. Abe	-	2	-	1973
P. Mansfield	8	3	1976	1975

Table 6: Direct and Indirect Patent Citations to 5 Candidates for 3 Time Periods

S-Curve Period	Applic. Year	Patents in Period	Abe Direct Cites	Damadian Direct Cites	Lauterbur Direct Cites	Mansfield Direct Cites	Weisman Direct Cites
Innovation	1972-82	35	9 (25.7%)	15 (42.9%)	3 (8.6%)	19 (54.2%)	0 (0.0%)
Growth	1983-90	1106	32 (2.9%)	72 (6.5%)	19 (1.7%)	111 (10.0%)	0 (0.0%)
Maturing	1991-03	3202	15 (0.5%)	171 (5.3%)	26 (0.8%)	91 (2.8%)	4 (0.1%)

S-Curve Period	Applic. Year	# Patents in Period	Abe Indirect Cites	Damadian Indirect Cites	Lauterbur Indirect Cites	Mansfield Indirect Cites	Weisman Direct Cites
Innovation	1972-82	35	30 (85.7%)	32 (91.4%)	11 (31.4%)	29 (82.9%)	0 (0.0%)
Growth	1983-90	1106	949 (85.8%)	962 (87.0%)	887 (80.2%)	980 (88.6%)	0 (0.0%)
Maturing	1991-03	3202	3014 (94.1%)	3027 (94.5%)	3011 (94.0%)	3038 (94.9%)	22 (0.7%)

Table 7: Key Early MRI Papers

(MRI Papers from 1970-80 with 25+ Total Citations and 3+ Citations from 1970-80 MRI Papers)

Author	Year	Journal	Title	Citations from 1970-80 MRI Papers	Total Citations
Damadian, R	1971	Science	Tumor Detection By Nuclear Magnetic Resonance	88	753
Freeman,R	1971	J Chem Phys	Fourier Transform Study Of Nmr Spin-Lattice Re	11	513
Cooke, R	1971	Biophys J	State Of Water In Muscle Tissue As Determined	2	88
Jonas,J	1972	Rev Sci Instrum	Nuclear Magnetic-Resonance Measurements At	3	76
Vaughan, RW	1972	Rev Sci Instrum	Simple, Low-Power, Multiple Pulse Nmr Spectro	4	94
Hollis, Dp	1972	Johns Hopkins Med	Nuclear Magnetic-Resonance Study Of Water In	12	49
Weisman,ID	1972	Science	Recognition Of Cancer In-Vivo By Nuclear Magn	40	141
Lauterbur PC	1973	Nature	Image Formation By Induced Local Interactions	52	1027
Damadian, R	1973	Ann Ny Acad Sci	Nuclear Magnetic-Resonance As A New Tool In C	21	85
Hollls,DP	1973	Cancer Res	Nuclear Magnetic-Resonance Studies Of Several	24	109
Damadian, R	1973	Physiol Chem Phy	Human Tumors By NMR	13	79
Schara,M	1974	Brit J Cancer	Characterization Of Malignant Thyroid-Gland T	4	34
Hinshaw, WS	1974	Phys Lett A	Spin Mapping - Application Of Moving Gradients	27	99
Lauterbur, PC	1974	Pure Appl Chem	Magnetic-Resonance Zeugmatography	23	89
Mansfield, P	1974	J Phys C Solid Sta	Image-Formation In Nmr By A Selective Irradiation	25	139
Damadian, R	1974	Physiol Chem Phy	NMR In Cancer .5. Electronic Diagnosis Of Cancer	10	33
Hazlewoo.CF	1974	J Natl Cancer I	Relationship Between Hydration And Proton Nu	17	95
Bovee, W	1974	J Natl Ancer I	Tumor Detection And Nuclear Magnetic-Resona	15	65
Damadian, R	1974	P Natl Acad Sci US	Human Tumors Detected By Nuclear Magnetic-R	19	130
Damadian, R	1974	Physiol Chem Phys	Biological Ion-Exchanger Resins .	4	26
Saryan LA	1974	J Natl Cancer I	Nuclear Magnetic-Resonance Studies Of Cance	20	130
Hollis, DP	1974	J Natl Cancer I	Nuclear Magnetic-Resonance Studies Of Cance	6	56
Medina, D	1975	J Natl Cancer I	Nuclear Magnetic-Resonance Studies On Human	7	75
Kumar, A	1975	Naturwissenscha	Imaging Of Macroscopic Objects By NMR Fourier	7	47
Ranade, SS	1975	Indian J Biochem	Bi Pulsed Nuclear Magnetic-Resonance Studies O:	5	30
Lauterbur,PC	1975	J Am Chem Soc	Zeugmatographic High-Resolution Nuclear Mag	10	97
Hollis, DP	1975	J Natl Cancer I	Nuclear Magnetic-Resonance Studies Of Cancer	13	72
Raaphorst, GP	1975	Biophys J	Nuclear Magnetic-Resonance Study Of Mammali	3	55
Eggleston, JC	1975	Cancer Res	Nuclear Magnetic-Resonance Investigations Of	12	75
Kiricuta,IC	1975	Cancer Res	Tissue Water-Content And Nuclear Magnetic-Re	8	102
Kumar, A	1975	J Magn Reson	NMR Fourier Zeugmatography	35	512
Mansfield, P	1976	J Phys C Solid State	Planar Spin Imaging By Nmr	9	33
Mansfield, P	1976	J Phys E	Sci Instru Fast Scan Proton Density Imaging By Nn	27	120
Damadian, R	1976	Physiol Chem Phys	Tumor Imaging In A Live Animal By Field Focusing	7	27
Mansfield, P	1976	Contemp Phys	Proton Spin Imaging By Nuclear Magnetic-Resm	7	28
Damadian, R	1976	Science	Field Focusing Nuclear Magnetic-Resonance (Fe	10	67
Gadian,DG	1976	P Natl Acad Sci US	Phosphorus Nuclear Magnetic-Resonance Stud	5	76
Beall, PT	1976	Science	Nuclear Magnetic-Resonance Patterns Of Intri	5	140
Damadian, R	1977	Brit J Cancer	Nuclear Magnetic-Resonance In Cancer .12. Appl	4	29
Hinshaw WS	1977	Nature	Radiographic Thin-Section Image Of Human Wris	18	149
Holland, GN	1977	J Magn Reson	F-19 Magnetic Resonance Imaging	9	59
Damadian, R	1977	Physiol Chem Phy	NMR In Cancer .16. Fonar Image Of Live Human-E	18	134
Blunt, JW	1977	Org Magn Resona	C-13 NMR Studies .69. C-13 NMR Spectra of Stero	3	654
Mansfield, P	1977	J Magn Reson	Planar Spin Imaging By NMR	10	79
Sehr, PA	1977	Biochem Bioph Res	Model Kidney-Transplant Studied By Phosphoru	3	85
Hollis, DP	1977	Biochem Bioph Res	Detection Of Regional Ischemia In Perfused Bea	7	82
Mansfield, P	1977	J Phys C	Solid Sta Multi-Planar Image-Formation Using Nmr	9	414
Mansfield, P	1977	Brit J Radiol	Medical Imaging By NMR	26	84
Jacobus, WE	1977	Nature	Phosphorus Nuclear Magnetic-Resonance Of Pe	12	201
Andrew, ER	1977	Phys Med Biol	NMR Images By Multiple Sensitive Point Method -	13	78
Damadian, R	1978	Cancer	NMR In Cancer .10. Malignancy Index To Discrimir	3	68
Damadian, R	1978	Naturwissenschaften	Field-Focusing Nuclear Magnetic-Resonance	9	38
Mansfield, P	1978	Brit J Radlol	Human Whole-Body Line-Scan Imaging By Nmr	11	57
Damadian, R	1978	Brit J Cancer	NMR In Cancer .13. Application Of Nmr Malignanc	4	42
Mansfield, P	1978	Phys Med Biol	Line Scan Image Study Of A Tumorous Rat Leg By	6	31
Bottomley, PA	1978	Phys Med Biol	RF Magnetic-Field Penetration, Phase-Shift And	9	191
Mansfield, P	1978	J Magn Reson	Biological And Medical Imaging By NMR	8	266
Hollis, DP	1978	J Magn Reson	Phosphorus Nuclear Magnetic-Resonance Stud	5	80
Hutchison, JMS	1978	J Phys E Sci Instru	NMR Imaging - Image Recovery Under Magnetlc-F	6	64
Hinshaw, WS	1978	Brit J Radiol	Display Of Cross-Sectional Anatomy By Nuclear	12	66
Damadian R	1978	Cancer	NMR In Cancer .11. Application Of NMR Malignanc	5	37
Sutherland, RJ	1978	J Phys E Sci Instru	3-Dimensional Nmr Imaging Using Selective Excit	6	73
Hinshaw, WS	1979	Brit J Radlol	Invivo Study Of The Forearm And Hand By Thin Se	9	68
Brunner, P	1979	J Magn Reson	Sensitivity And Performance Time In Nmr Imagin(;	6	105
Mansfield, P	1979	J Magn Reson	Selective Pulses In Nmr Imaging - Reply To Critic	3	44
Wolff S	1980	Radiology	Tests For Dna And Chromosomal Damage Induce	3	109
Holland, GN	1980	J Comput Assist Tom	Nuclear Magnetic-Resonance Tomography Of N	9	69
Moore, WS	1980	CT-J Comput Tomo	The NMR Cat Scanner - A New Look At The Brain	5	30

Table 8: Key Early MRI Papers of the Top Candidate Authors for MRI Discovery

Author	Year	Journal	Title	Citations from 1970-80 MRI Papers	Total Citations
Damadian, R	1971	Science	Tumor Detection By Nuclear Magnetic Resonance	88	753
Damadian, R	1973	Ann Ny Acad Sci	Nuclear Magnetic-Resonance As A New Tool In C	21	85
Damadian, R	1973	Physiol Chem Phy	Human Tumors By NMR	13	79
Damadian, R	1974	Physiol Chem Phy	NMR In Cancer .5. Electronic Diagnosis Of Cancer	10	33
Damadian, R	1974	P Natl Acad Sci US	Human Tumors Detected By Nuclear Magnetic-R	19	130
Damadian, R	1974	Physiol Chem Phys	Biological Ion-Exchanger Resins .	4	26
Damadian, R	1976	Physiol Chem Phys	Tumor Imaging In A Live Animal By Field Focusing	7	27
Damadian, R	1976	Science	Field Focusing Nuclear Magnetic-Resonance (Fe	10	67
Damadian, R	1977	Brit J Cancer	Nuclear Magnetic-Resonance In Cancer .12. Appl	4	29
Damadian, R	1977	Physiol Chem Phy	NMR In Cancer .16. Fonar Image Of Live Human-Bo	18	134
Damadian, R	1978	Cancer	NMR In Cancer .11. Application Of NMR Malignanc	5	37
Damadian, R	1978	Cancer	NMR In Cancer .10. Malignancy Index To Discrimin	3	68
Damadian, R	1978	Naturwissenschaften	Field-Focusing Nuclear Magnetic-Resonance	9	38
Damadian, R	1978	Brit J Cancer	NMR In Cancer .13. Application Of Nmr Malignanc	4	42
				215	**1548**
Hollis, DP	1972	Johns Hopkins Med	Nuclear Magnetic-Resonance Study Of Water In	12	49
Hollis, DP	1973	Cancer Res	Nuclear Magnetic-Resonance Studies Of Several	24	109
Hollis, DP	1974	J Natl Cancer I	Nuclear Magnetic-Resonance Studies Of Cance	6	56
Hollis, DP	1975	J Natl Cancer I	Nuclear Magnetic-Resonance Studies Of Cancer	13	72
Hollis, DP	1977	Biochem Bioph Res	Detection Of Regional Ischemia In Perfused Bea	7	82
Hollis, DP	1978	J Magn Reson	Phosphorus Nuclear Magnetic-Resonance Stud	5	80
				67	**448**
Lauterbur, PC	1973	Nature	Image Formation By Induced Local Interactions	52	1027
Lauterbur, PC	1974	Pure Appl Chem	Magnetic-Resonance Zeugmatography	23	89
Lauterbur, PC	1975	J Am Chem Soc	Zeugmatographic High-Resolution Nuclear Mag	10	97
				85	**1213**
Mansfield, P	1974	J Phys C Solid Sta	Image-Formation In Nmr By A Selective Irradiation	25	139
Mansfield, P	1976	J Phys C Solid State	Planar Spin Imaging By Nmr	9	33
Mansfield, P	1976	J Phys E	Sci Instru Fast Scan Proton Density Imaging By Nmr	27	120
Mansfield, P	1976	Contemp Phys	Proton Spin Imaging By Nuclear Magnetic-Resm	7	28
Mansfield, P	1977	J Magn Reson	Planar Spin Imaging By NMR	10	79
Mansfield, P	1977	J Phys C	Solid Sta Multi-Planar Image-Formation Using Nmr Spin Ec	9	414
Mansfield, P	1977	Brit J Radiol	Medical Imaging By NMR	26	84
Mansfield, P	1978	Brit J Radlol	Human Whole-Body Line-Scan Imaging By Nmr	11	57
Mansfield, P	1978	Phys Med Biol	Line Scan Image Study Of A Tumorous Rat Leg By	6	31
Mansfield, P	1978	J Magn Reson	Biological And Medical Imaging By NMR	8	266
Mansfield, P	1979	J Magn Reson	Selective Pulses In Nmr Imaging - Reply To Critic	3	44
				141	**1295**
Weisman,ID	1972	Science	Recognition Of Cancer In-Vivo By Nuclear Magn	**40**	**141**

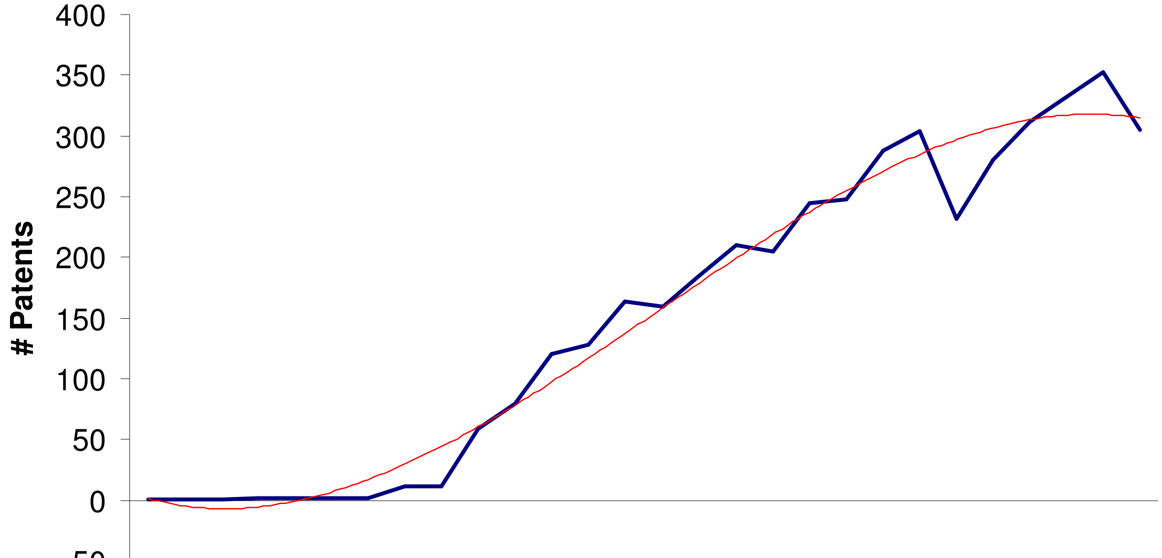
Table 9: Number and Percent of MRI Papers that Reference MRI Papers of Key Authors (Three Sets of MRI Papers from 1970-80)

	All 1970-80 MRI Papers (655 papers)				High Impact MRI Papers 1970-80 (135)				35 Key Author MRI Papers 1970-80			
Author	# Citing Papers	% of Citing Papers	# Indirect Citing Papers	% of Indirect Citing Papers	# Citing Papers	% of Citing Papers	# Indirect Citing Papers	% of Indirect Citing Papers	# Citing Papers	% of Citing Papers	# Indirect Citing Papers	% of Indirect Citing Papers
Damadian, R	109	17%	184	28%	57	42%	95	70%	23	66%	35	100%
Hollis, DP	52	8%	137	21%	34	25%	71	53%	12	34%	23	66%
Lauterbur, PC	66	10%	122	19%	38	28%	65	48%	14	40%	23	66%
Mansfield, P	58	9%	96	15%	34	25%	51	38%	15	43%	17	49%
Weisman, ID	38	6%	170	26%	25	19%	89	66%	13	37%	31	89%

Table 10: Number and Percent of MRI Papers that Reference MRI Papers of Key Authors (Two Sets of MRI Papers from 1981-90 and 1991-2003)

	High Impact MRI Papers 1981-90 (915)				High Impact MRI Papers 1991-2003 (4125)			
Author	# Citing Papers	% of Citing Papers	# Indirect Citing Papers	% of Indirect Citing Papers	# Citing Papers	% of Citing Papers	# Indirect Citing Papers	% of Indirect Citing Papers
Damadian, R.	52	5.7%	815	89.1%	4	0.1%	3579	86.8%
Hollis, DP	24	2.6%	814	89.0%	1	0.0%	3578	86.7%
Lauterbur, PC	45	4.9%	812	88.7%	12	0.3%	3579	86.8%
Mansfield, P	39	4.3%	811	88.6%	67	1.6%	3577	86.7%
Weisman, ID	10	1.1%	815	89.1%	0	0.0%	3579	86.8%

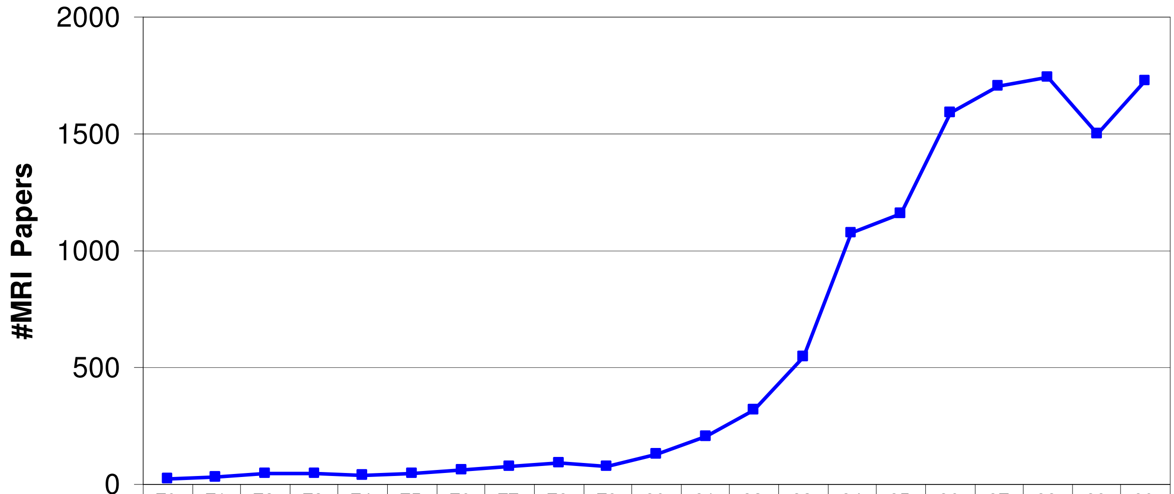
Figure 1: US MRI Activity over Time



72	73	75	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01
1	1	1	2	2	2	2	12	12	59	80	121	128	164	159	185	210	205	245	248	288	304	232	280	311	332	352	305

Application Year and # Patents

Figure 2: #MRI Papers by Year 1970-1990
(Superset of actual MRI Papers - See Text)



	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
	23	31	42	43	40	47	58	73	91	75	132	201	318	545	1074	1156	1588	1706	1745	1503	1726

Publication Year and #MRI Papers

Figure 3: Citation Connections Between Candidate's Earliest MRI Documents

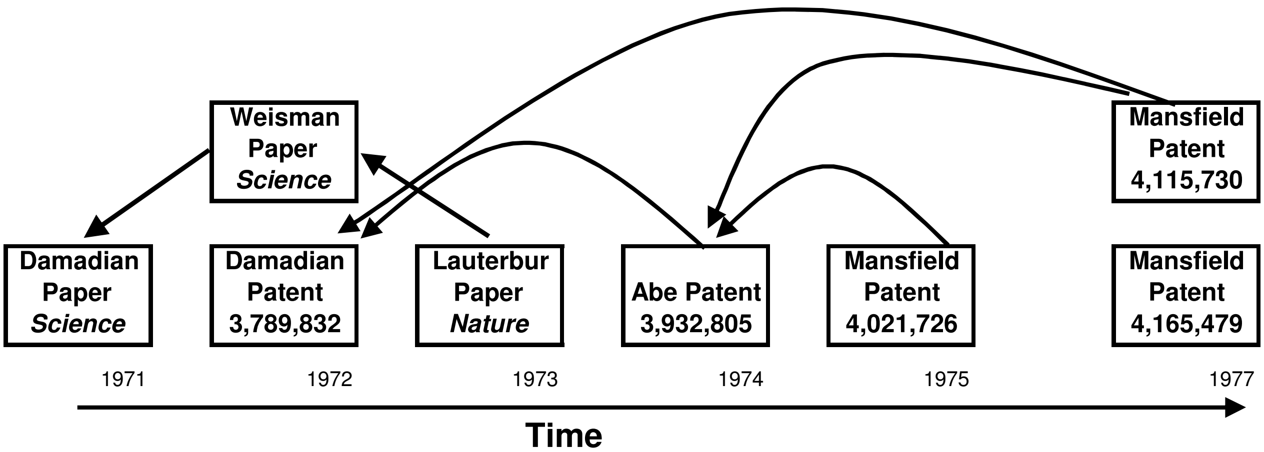


Figure 4: Referencing Patterns between 35 Key Author Papers

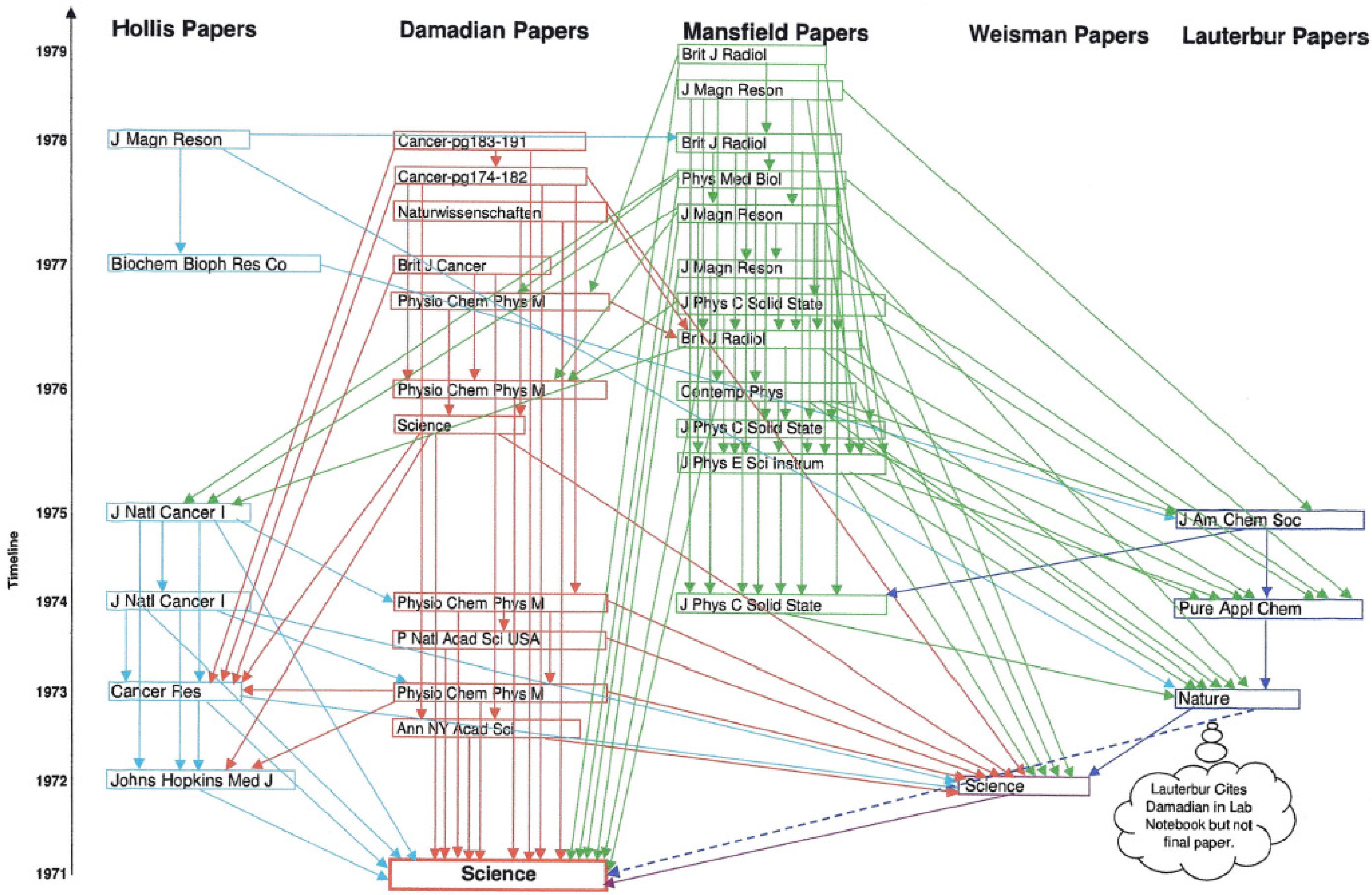


Figure 5: Referencing Patterns between 35 Key Author Papers (Self-Citations Removed)

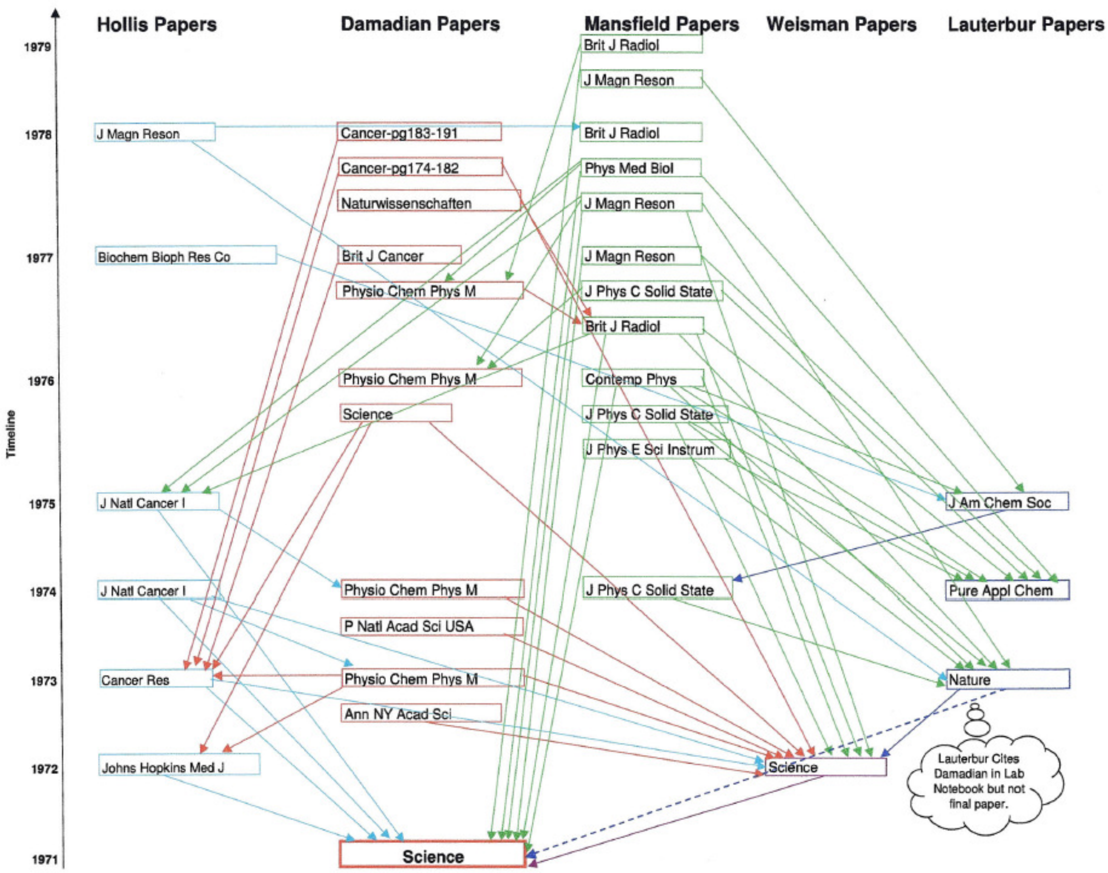


Figure 6: Cumulative Citations to Key Author Papers